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Paul Gierow & Greg Farmer (SRS), "Processes and Materials for Flexible PV Arrays"

IECEC 37th Conference **(Statement A)**
(???, 28 July – 02 August 2002) (Deadline: 28 July 2002 = NO rush authorized)

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PROCESSES AND MATERIALS FOR FLEXIBLE PV ARRAYS

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ABSTRACT

Electrical power is a major driver for nearly all classes of space missions and, consequently, the maximization of available power is an on-going challenge. Advanced missions within the Air Force are investigating the use of flexible PV array systems. The rapidly-evolving technology of flexible thin film PV cells lends itself particularly well to a flexible array concept. A parallel incentive for development of flexible PV arrays are the possibilities of synergistic advantages for certain types of spacecraft, in particular the Solar Thermal Propulsion (STP) Vehicle. The large sun-tracking solar concentrators of an STP vehicle present a highly-efficient support and pointing system for a large flexible PV array mounted on the deployed support torus, or the concentrator. The work performed focused on advancing the technologies that will improve and extend the application of solar arrays in a variety of space and aerospace environments. SRS Technologies performed analyses and demonstrated the feasibility of combining thin film PV array technology with methods to manufacture deployable membrane concentrators for solar thermal propulsion. Significant issues addressed were: the interconnection of the newly developed cells, proper thermal control, and electrostatic charge control of the complete system in the space environment. SRS demonstrated a self-metallizing polyimide concept for electrical interconnection of the backplane, and printing PV array interconnect circuitry directly on the thin film prior to lamination to the array. The actions accomplished indicated the feasibility and desirability of a flexible, high specific power, PV array concept and have established a firm foundation and roadmap for development of an operational concept.

INTRODUCTION

The use of large PV cell arrays is an efficient source for long-life missions. However, current satellites are power limited to ~15 KW due to the mass of deployable rigid arrays. Rigid panel arrays larger than 15 KW capacity place high demands on the satellite long-term attitude control systems. PV arrays are also limited by the cell power/mass efficiency and, later by the deleterious effects of exposure to the space environment. Significant improvements in power-to-mass ratio are possible merely by replacing the array honeycomb back-plate with a membrane backplane. Thin film amorphous silicon cells display approximately 1/5th the efficiency, but only 1/40th the areal density of rigid-mounted, state-of-the-art, dual junction crystalline cells. This offers the potential for an improvement in array power-to-mass ratio. Further improvements can be achieved by incorporating printed interconnections into the membrane backplane, and developing methods to extend the operating life of systems in space. This paper presents the work performed by SRS Technologies to address these key technology development areas. SRS demonstrated the feasibility of combining the thin film PV array technology with methods to manufacture deployable membrane concentrators for solar thermal propulsion. SRS also extended preliminary work in encapsulating methods with amorphous silicon cells that was performed by Simburger (2001). SRS identified an approach for mitigating arcing and static charge build-up on PV arrays. This discovery was made from work done in developing semi-conducting, optically-clear polyimides. SRS also developed a self-metallizing polyimide processes for making electrical interconnections of the backplane (Southward, 1996). The feasibility of printing PV array interconnect circuitry directly onto thin film, prior to lamination to the PV array was also demonstrated. The actions accomplished support the feasibility of the flexible high specific power PV array concept, and establish a foundation and roadmap for further development of the concept to an application-ready status.

PV ARRAY INTEGRATED WITH DEPLOYABLE CONCENTRATOR

SRS considered the advantages and disadvantages of integrating flexible arrays with an inflatable membrane concentrator. SRS evaluated a pointing array concept versus a large-area omni directional concept. The non-pointing array is convenient in some respects, but carries the following penalties: (a) approximately 4 times as much cell

area is needed compared with a pointed array, and (b) multiple variable-gain DC to DC converters are required to boost the output voltage of all but the most optimally oriented cell-strings. In the application of PV arrays with the solar propulsion vehicle, a very favorable synergy is available. The large torus-supported solar concentrator is used for propulsion purposes during LEO to GEO transfer, and thereafter its "back" side is available to support a large solar array. Within reasonable limits of spacecraft attitude, the concentrator pointing system can be utilized to point the solar array such that it is maintained normal to the sunlight direction. SRS evaluated several options for PV array mountings focused around the SOTV application. A discussion of these options follows:

PV Cells on the Concentrator Support Torus

The support torus provides a large surface area for mounting cells with minimal impact to the shape of the concentrator. SRS designed a torus mounted array to operate in two orientations, each 180° apart, relative to the sun, and laid out the cell strings to start and stop at the lines on the torus that are 90° from the direction of the sun. For an optimum-oriented array, any one cell string cannot extend beyond an ~20° radial band on the torus surface, otherwise the least-illuminated cells will force the entire string to operate at a non-optimum point on the cell loading curve. If two or more cells of a string are under-illuminated the entire string must operate at reduced current output in order that the strings output voltage can reach the output bus voltage. A variable-gain DC to DC converter could be used to avoid this problem, but would increase complexity, weight, and expense. For these reasons a torus is an inefficient substrate for a large PV array. For providing the modest electrical power required during orbit transfer, a thin film PV array mounted on the concentrator torus may be adequate. Since the concentrator points toward the sun, an array can be located on the most favorable regions of the torus, as shown in **Exhibit 1**. On a 4 x 6 meter concentrator, an optimized three square meter PV array could be mounted on the torus.

PV Array Blanket Mounted On Concentrator

In order to achieve reasonable performance using a solar concentrator to support a PV array, the concentrator pointing system must be used to maintain the PV array at 90° ±5° from the sun direction. A curved array is less efficient than a flat array, and even a flat array will be quite inefficient unless it is oriented at nearly 90° to the sun. PV cells mounted directly to or incorporated in the mirror film cause distortion of the concentrator figure. To avoid this, the cells could be mounted onto a doubly-curved substrate, such as an inflatable "blanket" behind the concentrator mirror, as shown in **Exhibit 2**. This option adds a complexity to the concentrator inflation system, and will disturb the symmetry or force balance between canopy and mirror film. To mitigate this, the array would have to depend on its own material stiffness to maintain its shape after inflation. This is a significant challenge since a mismatch of material CTEs, and deposition stresses typically cause membranes to curl. This approach would also impact the printed bus line design, and layout. The bus lines printed on the backing-film will be designed for flexibility, and stowage, not for rigidity. Line placement will be laid out for optimum electrical inter-connections of the cells. If the array is doubly-curved, with "great circle" fold lines between cells, the cell-groups will not be uniform in size or in shape over the array. Furthermore, it is more difficult to fabricate doubly-curved cells than flat cells. Also, to mount flat cells on a doubly-curved backing-film, and achieve the thermal contact required to keep the cells cool, requires that the backing-film be faceted or geodesic in shape. For all of these reasons we concluded that a membrane-supported, flat array, mounted on the backside of the concentrator is the most promising concept. A photograph of the test concept fabricated to demonstrate the geometries is shown in **Exhibit 3**. One final mounting issue involves clearance between the array and the mirror. In some applications the depth of the mirror and canopy may extend beyond the cross-sectional thickness of the torus. For these applications the mirror would come in contact with a flat array supported by the torus. To resolve this, a "stand-off" interface between the torus and the array would be required. Such a stand-off would be advantageous from the standpoint of solar thermal thruster plume clearance.

POLYIMIDE ENCAPSULATION TECHNOLOGIES

Solar arrays deployed in space will be immersed in conducting space plasma, consisting of ions and

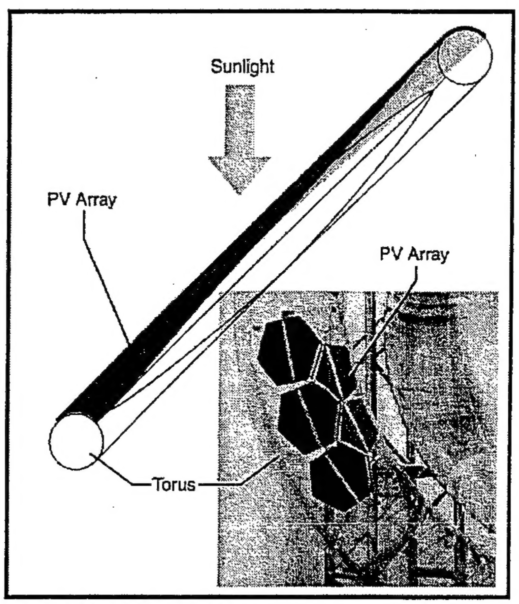

EXHIBIT 1 PV ARRAY MOUNTED ON THE ISOLATED REGION OF THE TORUS IN PHASE I

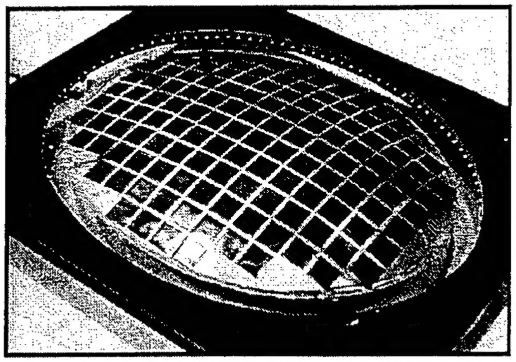

EXHIBIT 2 PV ARRAYS MOUNTED TO THE BACK OF A DOUBLY-CURVED MEMBRANE IN PHASE I

electrons and an imbedded magnetic field, which can degrade array electrical performance, and reduce array life expectancy. The most common and deleterious effects are: leakage currents (Stevens, 1979; Parker, 1980), pin hole (snap-over) phenomena, plasma induced charging, and solar UV-induced charging. Solar arrays have large areas and consequently have significant capacitance. As a result of the stored energy, discharges ignited on arrays may achieve power levels that are sufficient to emit high levels of electromagnetic noise that can interfere with on-board systems and control logic (Wrenn et al., 1993).

An approach to resolving environmentally-induced problems is to isolate the array from the environmental influences. The complexity of a laminated array structure, the interconnects, and electrical circuitry make this difficult. The piece-wise isolation of these various components (e.g., placing cover glasses on the PV cells, etc.) adds to the complexity and mass of the array. This approach has not completely alleviated the problems, and in some cases has created additional outgassing and contamination issues. The technical approach evaluated involves stripping away the complexity of piece-wise solutions and encapsulating the array in a single, unbroken semi-conducting thin film laminate. The film will function as the inter-cell insulation and static charge dissipater, and may serve as a cover glass for some missions. Since the array is encapsulated in an unbroken monolithic dielectric film there are no complex junctions between various surface materials, no vent holes between interfaces to create electrical discharges and arcs, and the whole structure will be less massive, mechanically and electrically simpler and, therefore, more robust.

Materials Properties Determination

SRS identified membrane encapsulate characteristics required to effectively isolate the solar array from the space environment, while remaining transparent in the required solar band. SRS has worked with NASA, the Aerospace Corporation, and Physical Sciences Inc. on tests to quantify the darkening effects of materials exposed to the space

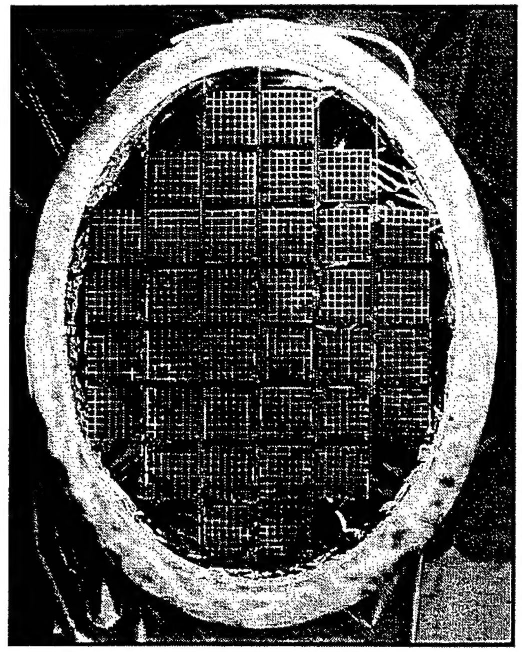

EXHIBIT 3
PHASE I FLAT MEMBRANE PROTOTYPE

environment, and the effects atomic oxygen (AO) has on material mass loss and optical transparency loss. **Exhibit 4** depicts the resulting transparency loss for an inorganic (SiOx) coated film of CP1 material. The material did not loose mass or optical transparency during this set of experiments.

Electrical

The encapsulation material must stand off the voltage developed between the surface of the insulating thin film and the solar array components below. This potential will be the sum of the voltage developed by the solar array string and that imposed on the insulating surface by the space environment.

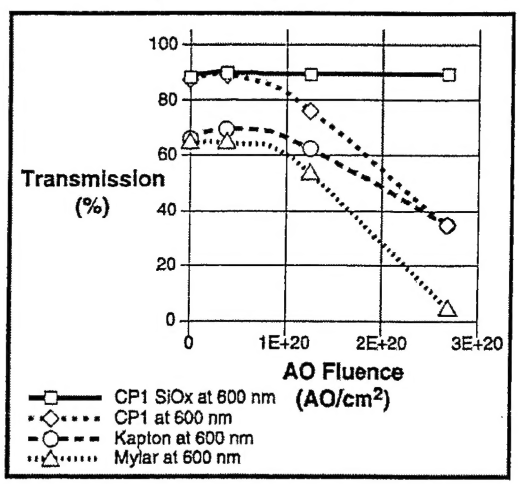

EXHIBIT 4
PROPERLY COATED POLYMER MATERIAL RESISTS AO EROSION AND RETAINS TRANSMISSIVITY

While the solar array-generated potentials are typically on the order of 100 V or less, the surface charging potentials particularly in hot plasma, may be on the order of several kV. The dielectric strength of the film must be sufficient to hold off this potential in space, over a wide range of temperatures and in the presence of a plasma and ionizing radiation. Covering the spacecraft surface with a thin film having a sheet resistivity on the order of 10^{10} ohms per square, will limit charging voltages to acceptable levels. SRS has manufactured CP1 colorless polyimide film, doped with carbon nanotubes that demonstrated sheet resistivities in the desired range with little impact on optical density. A dual layer encapsulation may be needed, as the presence of the nanotubes may degrade dielectric strength enough to require separation of the functions of electrical isolation and static discharge. SRS has cast films with adequate conduction levels at thicknesses in the range of 1 micron.

Optical

For PV operation the materials must be transparent in the solar spectrum, and maintain transparency within predicted limits over the planned mission lifetime. SRS evaluated the response curves of film degradation to cell performance. **Exhibit 5** depicts the transmission curve of a CP1 polyimide material before and after exposure to UV and proton radiation at dosage levels simulating the GEO environment. The efficiency of flexible GaAs/Ge cells can be calculated based on the air mass zero (AM0) solar spectrum, the spectral quantum efficiency of the cells, and the CP1 spectral transmission. The quantum efficiency of this cell rises rapidly to over 90% at a wavelength of 500 nm, and maintains this level out to about 800 nm. Although the cell experiences some degradation from radiation exposure, only changes in CP1 transmission were included in our analyses. Because CP1 transmission decreases due to radiation effects over a 5 year GEO exposure, a beginning-of-life (BOL) and an end-of-life (EOL) efficiency is calculated. The largest CP1 transmission losses due to radiation effects occur in the UV end of the spectrum below 0.5 mm, as shown in A and B in Exhibit 5. The effects of these losses on cell efficiency are minimized since the cells have low quantum efficiency at UV wavelength, and high efficiency in the 0.5-0.8 mm range. The resulting overall spectral power for the CP1 encapsulated flexible PV cells at BOL and EOL are shown in C and D in Exhibit 5. Bare GaAs/Ge cells have a total integrated power conversion efficiency of 19%. The total power conversion efficiency for the CP1 encapsulated cells (obtained by integrating the overall spectral efficiencies and adding the result to the non-spectral efficiencies in the cell) at BOL is 16.6% (similar to the level achieved with a glass cover) and 14.3% at EOL. The loss in cell efficiency due to CP1 darkening over a 5-year period is ~2%.

PV ARRAY BACKPLANE DEVELOPMENT

Typical flight-like PV arrays are mounted on metal, non-foldable, honeycomb panels of significant mass,

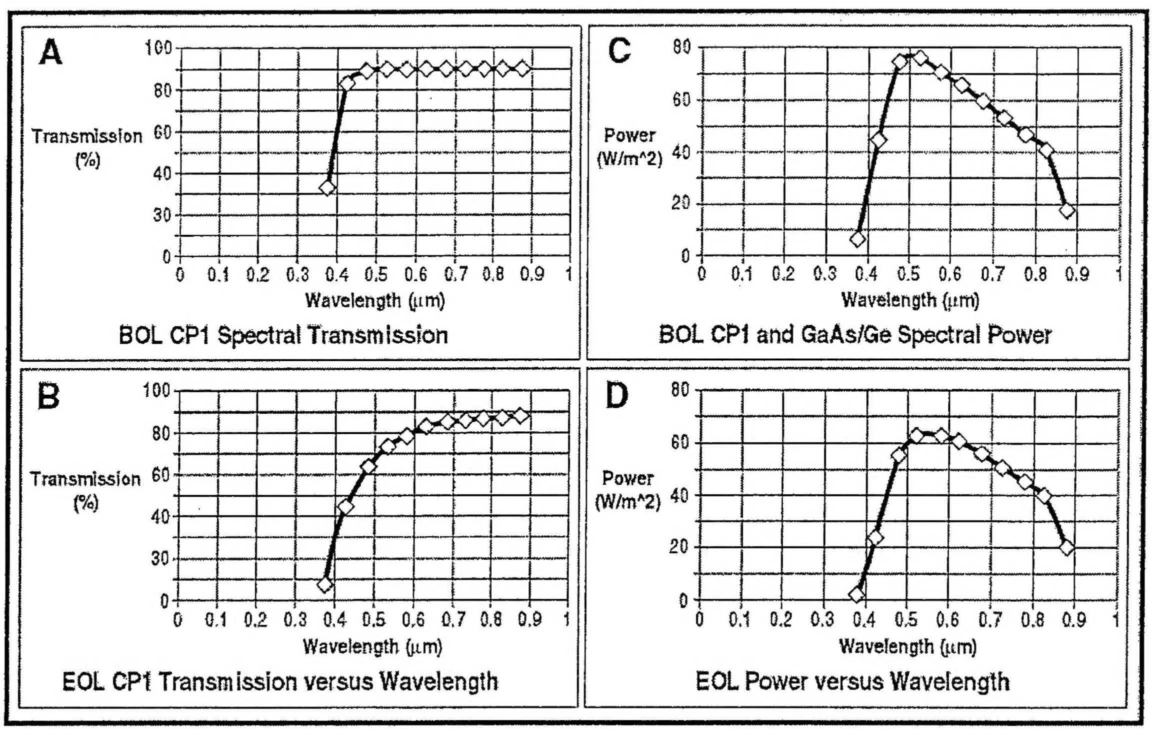

EXHIBIT 5 END OF LIFE EFFECTS OF POLYIMIDE MATERIAL ON SPECTRAL RESPONSE OF SOLAR CELL

which utilize discrete wires for interconnection. A tensional thin polyimide membrane that mechanically supports and electrically interconnects the elements of a PV array can significantly reduce the power-per-mass, and power-per-stowed-array volume of typical arrays. SRS developed a concept for a polyimide membrane, containing printed interconnection lines, that meets the mechanical support, heat sink, and stowage goals for cells or cell-strings. In tests, high electrical conductivity, and good adhesion were obtained using heat-reducible metal ion salts with polyimide film substrates. Subsequent electroplating of copper was demonstrated on the printed circuit leading to a single piece film with embedded electrical connections. Thermo-compression bonding of films was found to be the most desirable means of laminating polyimide films to imbed the printed wiring harness. This process eliminates the need for photolithography etching of plated polyimide substrates.

Electrical Interconnection.

Interconnection of PV cells or cell-strings is most efficiently performed by use of printed wiring imbedded in the supporting flexible backplane. Current arrays utilize wiring assembled wire-by-wire, bonded to the array support, and encapsulated. Printed wiring, which is integral to a multilayer flexible backplane, will simplify array assembly, reduce wiring errors, improve flexibility for stowage, and reduce mass of the backplane.

Traditionally, wiring imbedded in flexible membranes are made using photo-etched thin copper laminated to a film, then thermo-compression bonding films to encapsulate the wiring. SRS demonstrated a process of computer-controlled printing of a polyimide solution containing a heat-reducible metal salt. The chemical reaction of this process is shown in **Exhibit 6.** This patented technique was modified by SRS so

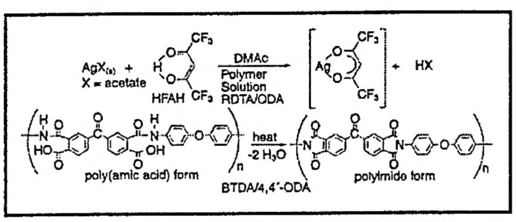

EXHIBIT 6 SELF-METALLIZING REACTION MECHANISM

that the metallic solution can be applied to a polyimide film (Sangyoji, 1996). The solution is reduced to the conductive layer by heating. This process can be used to deposit a seed layer for follow-on electroplating. Initial results showed promise in using a modified piezoelectric print head to accurately print conductive circuits on dielectric polymer substrates. SRS demonstrated an automated conductive printing system consisting of a servomotor driven X-Y coordinate table, a piezoelectric print head, a solution feed system, and a computer controller. The head has four independent piezoelectric (PZT) quadrants, each with 64 addressable channels combining to provide a total of 256 jets. The nozzles from the four quadrants are arranged into a single line at .011 inches between the nozzles.

During initial testing of the printing system conductive lines were printed utilizing a single port on the print head. To make consistent, conductive narrow lines, several passes were necessary to deposit enough conductive solution. A convection dryer was used to dry the solution to the polyimide. A high temperature heat source was used to fully activate the metallization process. These tests were repeated using multiple jets on the print head to form a series of parallel conductive traces similar to what would be found on a circuit board. **Exhibit 7** shows a sample of the parallel conductive traces that were printed. The success of these tests shows that printing of larger and more complicated conductive geometries should be possible. By combining this technology with the other PV array advances, fabrication of a flexible PV array with membrane circuits should be possible.

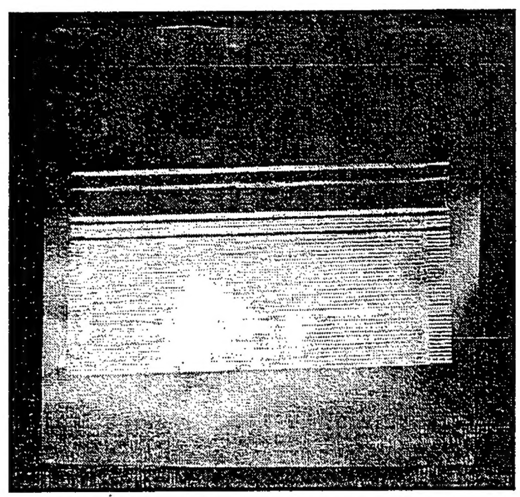

EXHIBIT 7 PARALLEL CONDUCTIVE LINES

Mechanical Support and Thermal Control

In microgravity the main mechanical stresses and deformation experienced by the arrays will be due to station-keeping and attitude control maneuvers. Strong bonding of the PV elements to the flexible backplane is critical to counter peel stresses caused when materials with different flexural properties are bonded. Also, polyimides have modest bulk thermal conductivity, but very high conductance in films on the order of 50 microns thick, therefore for thermal control it is critical to assure void-free bonding of the PV elements to the flexible backplane without the need of thick, thermally resistive adhesives. SRS demonstrated strong membrane bonding using a thermo-compression process, achieved by vacuum-bagging in an autoclave.

CONCLUSIONS

Though the dimensions and sun orientation of an SOTV vehicle provide advantages for PV array power generation, the mounting limitations of the torus, and the sensitivity of the concentrator limit the available options for integrating an array. The most promising option would be an flat array, mounted offset on the backside of the torus. With respect to array encapsulation technologies, a concept using an monolithic polyimide dielectric film to minimize the need for complex junctions between surface materials, eliminate vent holes between interfaces, simplify mechanical and electrical design, and reduce mass was developed and tested. The test results indicated that the film material properties can be tailored to meet all the encapsulation needs, ultimately leading to a more robust array design. Finally, the work to develop an integrated array backplane demonstrated techniques for self-metallizing polyimide, film electroplating, and precision printing of conductive lines directly on a film. These techniques coupled with a thermo-compression bonding process also demonstrated, form the foundation for an integrated, thin film, flexible, backplane concept.

ACKNOWLEDGEMENTS

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